

Advanced Composites in Engineering Structures

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Lecture VII: Durability and long-term behaviour of composites

Outline

1. Introductory aspects
2. Durability
3. How durability can be addressed by the European Standard CEN/TS 19901:2022
4. Viscoelasticity
5. How viscoelasticity can be addressed by the European Standard CEN/TS 19901:2022

Section 1

Introductory aspects

Durability and long-term behaviour of composites

Introductory aspects

ChatGPT: What is the definition of durability of FRP composites

?

The durability of **FRP (Fiber Reinforced Polymer) composites** refers to their **ability to maintain mechanical and structural integrity over an extended period** under various environmental conditions, loads, and external factors.

Durability in FRP composites is typically assessed by how well they resist degradation caused by factors like:

- **Environmental exposure**
- **Mechanical stresses**
- **Corrosion resistance**
- **Creep and fatigue**

The durability of **FRP composites** plays a critical role in **their application**, especially in industries like **aerospace, civil engineering, automotive, and marine**, where long-term performance and minimal maintenance are required.



Durability and long-term behaviour of composites

Introductory aspects

Service life of composites in different sectors

*“The structure shall be designed such that deterioration over its **DESIGN WORKING LIFE** does not impair the performance of the structure below that intended, having **DUE REGARD TO ITS ENVIRONMENT AND THE ANTICIPATED LEVEL OF MAINTENANCE.**”*



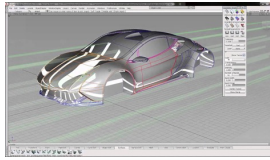
Source: EuCIA – “Reimagining end-of-use composites as a new resource”

Durability and long-term behaviour of composites

Introductory aspects

□ Durability - Complexity of phenomena

- Although **composite materials have been successfully used** in the construction, automotive, marine, wind energy, and aerospace sectors, **there are critical differences among each application** in terms of:
 - Loading conditions
 - Environmental conditions
 - Types of materials used
 - Processes
- A **huge variety of different constituent materials** are commercially available.
- In many situations, **there is an absence of standards** for the **characterization of the durability**.
- Difficulties in testing: **artificial accelerated** *versus* **real/natural aging**.



Introductory aspects

- **DEGRADATION FACTORS** are all **agents** that act on the material, component or structure and that may **cause alterations on its performance**. The main degradation factors can be mainly classified according to two categories:

Environmental degradation factors	Mechanical degradation factors
<ul style="list-style-type: none">▪ Moisture▪ Chemicals▪ Thermal effects▪ UV exposure	<ul style="list-style-type: none">▪ Static loading: creep, relaxation▪ Dynamic loading: fatigue, vibrations, impact

Introductory aspects

- **DEGRADATION MECHANISMS** are characterized by a sequence of **chemical, mechanical and/or physical changes**, leading to the **alteration of one or more mechanical properties** of the material, component or structure in a harmful way **when exposed to a degradation factor or a combination of them.**




Examples of **degradation mechanisms**:

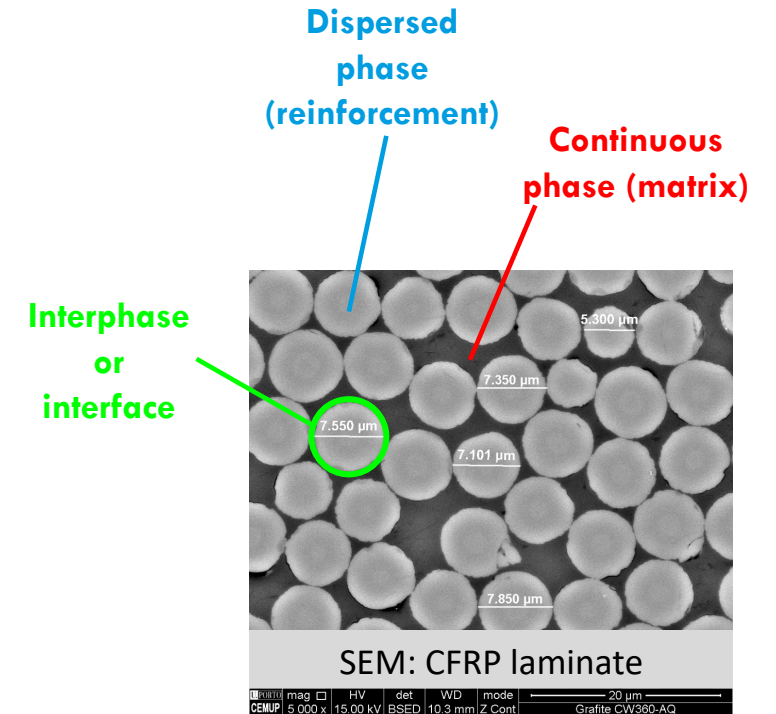
- **Physical:** Plasticization, Relaxation
- **Mechanical:** Debonding
- **Chemical:** Hydrolysis, Leaching

Durability and long-term behaviour of composites

Introductory aspects

□ Factors influencing the durability

-  **Design**
 - **Constituent materials**
 - Type of polymeric matrix
 - Type of fibre reinforcement
 - Fibre-matrix interface
 - **Special measures** (e.g. protective systems)
-  **Production**
 - **Manufacturing process** (e.g. temperature, moisture, consolidation pressure in curing procedures)
 - **Quality control** (installation in construction site)
-  **Use**
 - Type of **loading**
 - **Environmental exposure** (**temperature, moisture, chemicals, UV radiation**)
 - **Maintenance** and type of **use** during service life



Source: CEN/TS 19101:2022 (E)

Section 2

Durability

Section 2.1

Environmental degradation factors

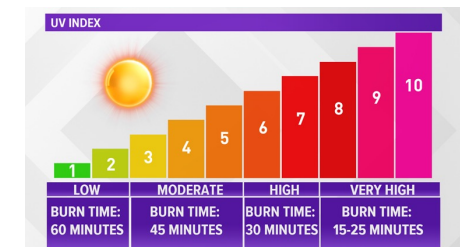
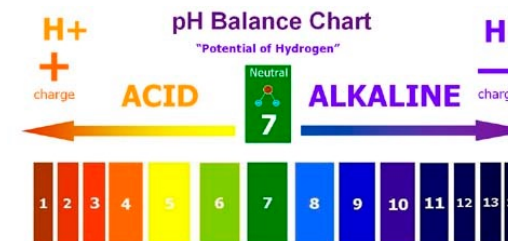
Durability and long-term behaviour of composites

Durability

□ Environmental degradation factors

The main environmental degradation factors affecting composites, acting in isolation or in combination are:

- **Temperature**
- **Moisture**
- **Chemicals**
- **Ultraviolet (UV) radiation**



Durability - Temperature

- ❑ Normally, **thermal effects of composites** can be split in:
 - Service temperature conditions (**below T_g - value °C**)
 - Thermal cycles
 - Sub-0 °C temperatures
 - Freeze-thaw cycles

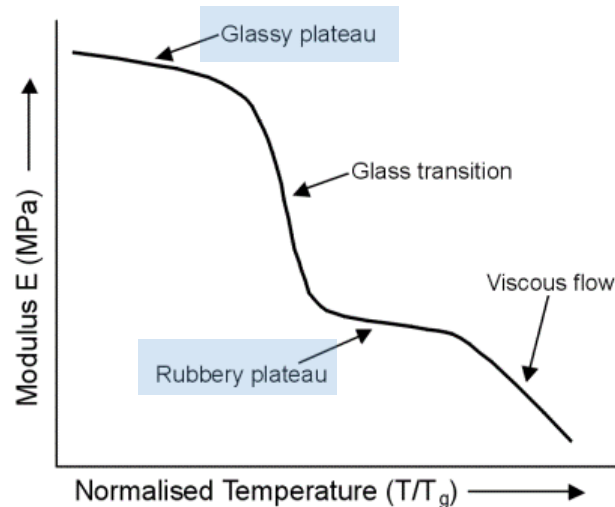
- ❑ In general, the **existing knowledge** on the thermal effects in composite materials **is rather limited...**
However, for specific products and applications may be comprehensive.

- ❑ Additionally, **test methods** adopted in the studies **vary significantly**, with respect to
 - the constituent materials (fibre and resin),
 - manufacturing processes,
 - type and exposure conditions, and,
 - characterisation techniques.

Durability - Temperature

□ What is **glass transition temperature**?

- **Glass transition temperature** (T_g) is the **temperature range** where the polymer substrate changes from a **rigid glassy material** to a **soft likely rubber** (not melted) material, and is usually measured in terms of the stiffness, or modulus.



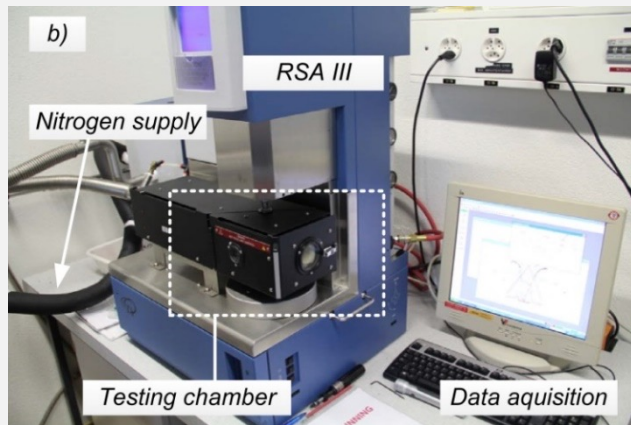
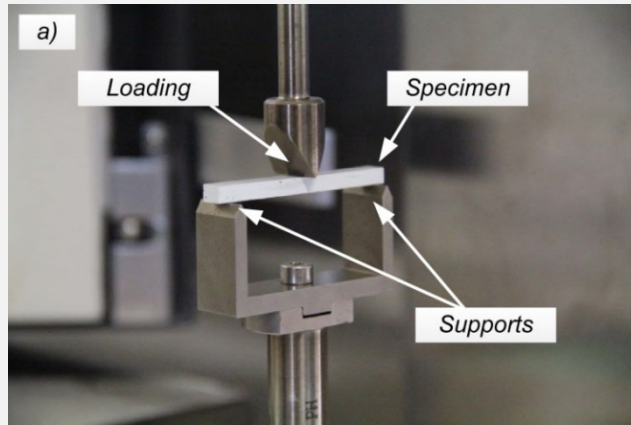
Techniques for assessing the T_g :

- **Differential Scanning Calorimetry (DSC)**
- **Thermal Mechanical Analysis (TMA)**
- **Dynamic Mechanical Analysis (DMA)**

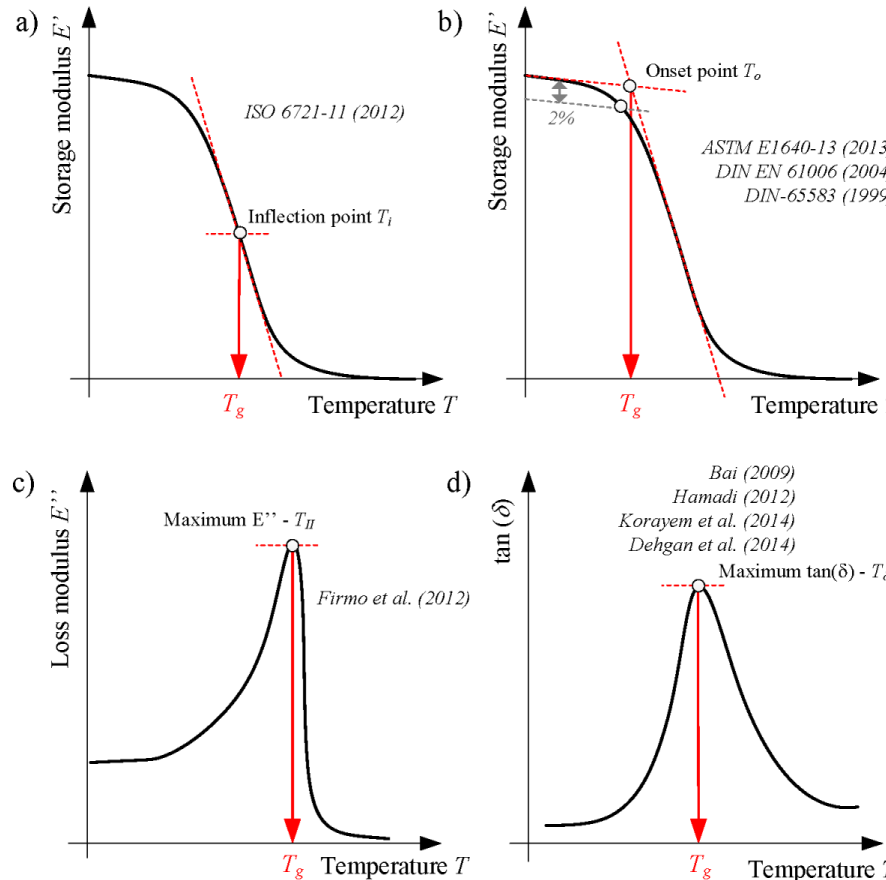
Durability and long-term behaviour of composites

Durability - Temperature

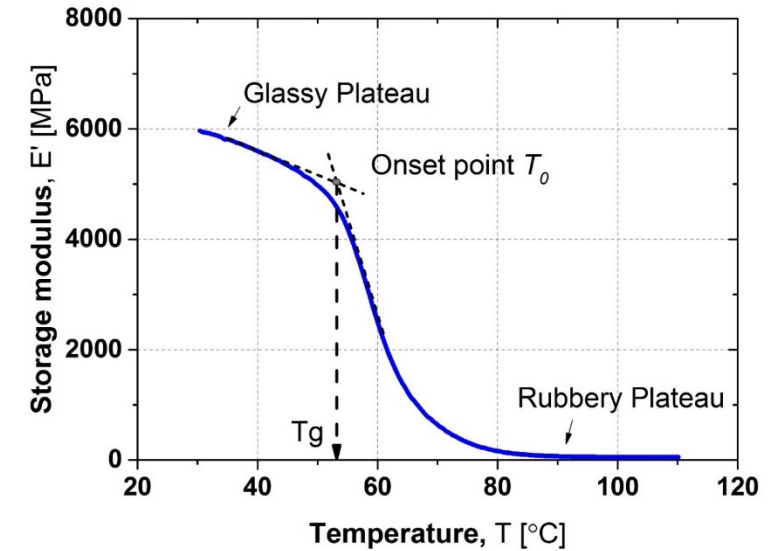
□ What is **glass transition temperature**?



(Michels et al. 2015)



Example of a DMA test of an epoxy adhesive

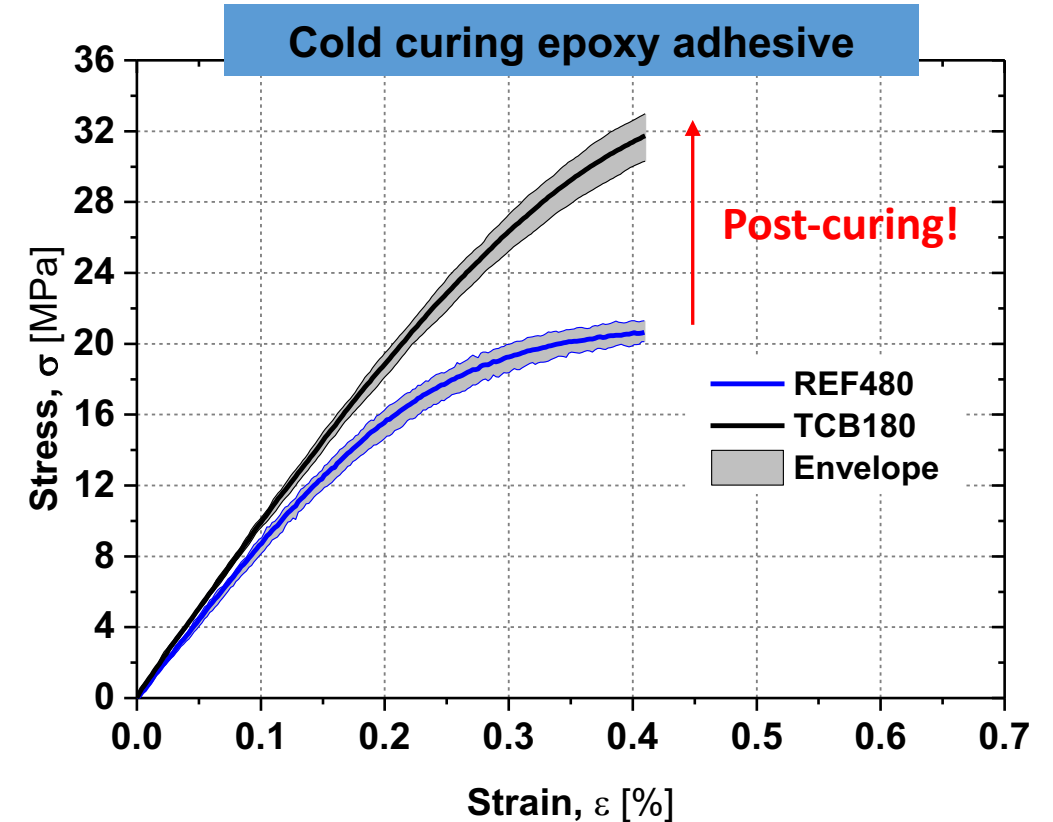


- Polyester → 70 °C to 95 °C
- Vinylester → soften above 90 °C
- Cold curing epoxy → 50 °C to 70 °C
- Epoxy of high T_g → 230 to 260 °C

Durability - Temperature

❑ Post-curing effect

- **Post-curing** occurs when a polymer material is submitted to a **temperature higher** than the one at the **first cure**, thus increasing the curing degree (*). Normally, the **post-curing** phase increases the **mechanical properties of the material**.
- **Post-curing** is observed when the **temperatures** in the polymer material temporally **exceed the T_g** . T_g also **increases** with **post-curing**.



$$f_{\text{epoxy}} \nearrow +58\%$$

$$E_{\text{epoxy}} \nearrow +24\%$$

(*) The curing degree describes the conversion rate achieved during **crosslinking reactions** (curing). In macromolecular chemistry, crosslinking refers to reactions in which a large number of individual molecules are linked to form a three-dimensional network. Linkage can be achieved either by direct setup of macromolecules or reaction to the already existing polymers.

Durability - Temperature

□ Effects of composites

- **Elevated temperatures** – when approaching or exceeding the T_g :
 - Post-curing of the polymer matrix may occur after thermal exposure with beneficial effects
 - Reduction of elastic and strength properties (mainly due to softening of the polymeric matrix)
 - Increase of viscoelasticity of polymeric resins
 - Increased of susceptibility to moisture incorporation
 - Degradation of the fibre-matrix interface

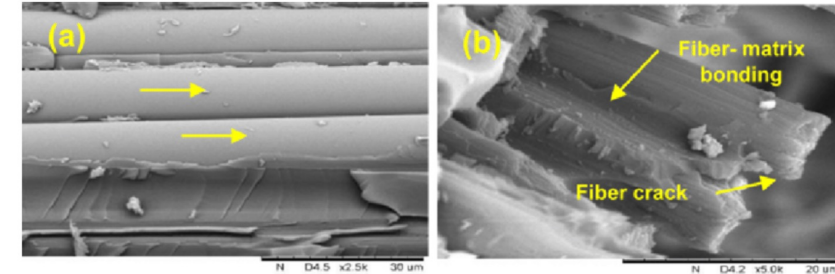
Note: by cooling the polymeric matrix from temperatures above to below T_g result into a full recovery of its mechanical properties.

- **Low temperatures:**
 - Generally, no significant change in strength
 - Matrix hardening (lower deformability) and microcracking
 - Degradation of fibre-matrix bond

Durability and long-term behaviour of composites

Durability - Temperature

□ Effects of composites



- **Thermal cycles:**
 - Degradation of fibre-matrix bond (due to mismatch in CTE of fibers and matrix)
- **Freeze-thaw cycles (in combination with moisture and thermal cycles):**
 - Degradation of fibre-matrix bond (due to mismatch in CTE of fibers and matrix)
 - Increased degradation due to cyclic expansion and contraction (volumetric changes) of entrapped water

Coefficient of linear thermal expansion [$10^{-6} K^{-1}$]

Direction	E-Glass	S-Glass	Basalt	HM-Carbon	HS-Carbon	Aramid	Polyester	Vinylester	Epoxy
s1	5	3	8	-0,4	-0.8	-2.0	30 - 200	30 - 50	50 -100
s2	5	3	8	10.0	10.0	54.0			

Durability and long-term behaviour of composites

Durability - Temperature

□ Low temperatures (LT) and cryogenic temperatures (CT)

Description	[K]	[°C]	Category
Room temperature	296	23	RT
Design temperature for Arctic conditions	223	-50	LT
Design temperature for aircraft components	216	-57	LT
Solid carbon dioxide (dry ice)	195	-78	LT
Design temperature for cubesats	188	-85	LT
Lowest temperature measured on Earth	184	-89	LT
Liquid methane (LCH ₄) or natural gas (LNG)	111	-162	CT
Lowest temperature in low Earth orbit (LEO)	103	-170	CT
Liquid oxygen (LOX)	90	-183	CT
Liquid nitrogen (LN ₂)	77	-196	CT
Liquid hydrogen (LH ₂)	20	-253	CT
Liquid helium (LHe)	4.2	-269	CT
Temperature in empty space	3	-270	CT
Absolute zero	0	-273	CT

Durability - Temperature

□ Low temperatures (LT) and cryogenic temperatures (CT)

- The **tensile** elastic modulus and strength of the matrix tend to increase with decreasing temperature.
- Similarly to tension, the **compressive** modulus and strength of the resin increase, and the failure strain decrease with decreasing temperature.
- The **shear** behavior of composites is primarily controlled by the behavior of the matrix.
- Fracture **toughness** is defined as the damage tolerance of materials as their ability to resist crack propagation. Improved fracture toughness has been observed at cryogenic temperatures.
- The general trend according to literature, is decreasing composites **impact** performance with decreasing temperature.

Source: Sápi, Z & Butler, R 2020, 'Properties of cryogenic and low temperature composite materials – A review', *Cryogenics*, vol. 111, 103190.

Durability - Temperature

□ Mitigation measures

To avoid undesired degradation of composites, the following aspects should be considered:

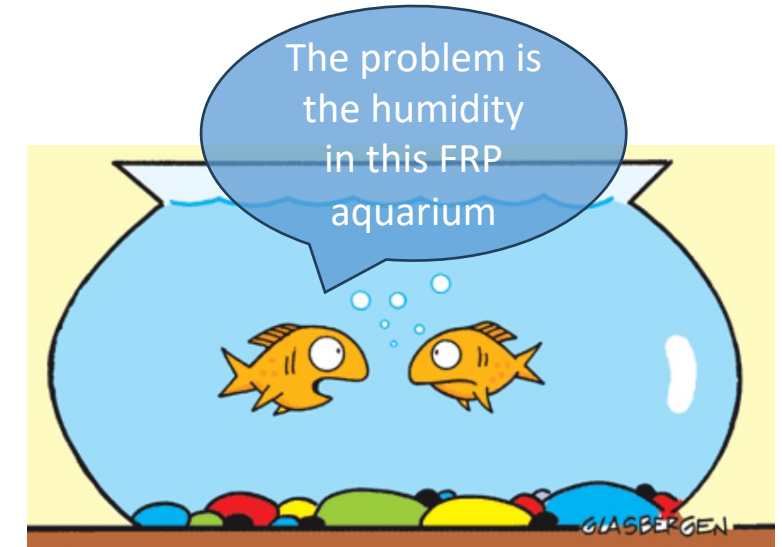
- Fibres should be completely and well covered by resin;
- Composites should not have cracks, either on the surface or in throughout thickness;
- Composites should not have voids;
- The production process should guarantee good cure of the resin;
- Service temperatures far from T_g ;
- Good compatibility in terms of coefficient of thermal expansion (CTE) between matrix and fibres.

Durability and long-term behaviour of composites

Durability - Moisture

❑ Typically, **moisture** includes direct contact to:

- Rain
- Humidity
- Moisture
- Immersion in aqueous solutions
- Among others...



❑ Moisture causes **changes** in the **physical**, **mechanical** and **chemical** properties of composites.

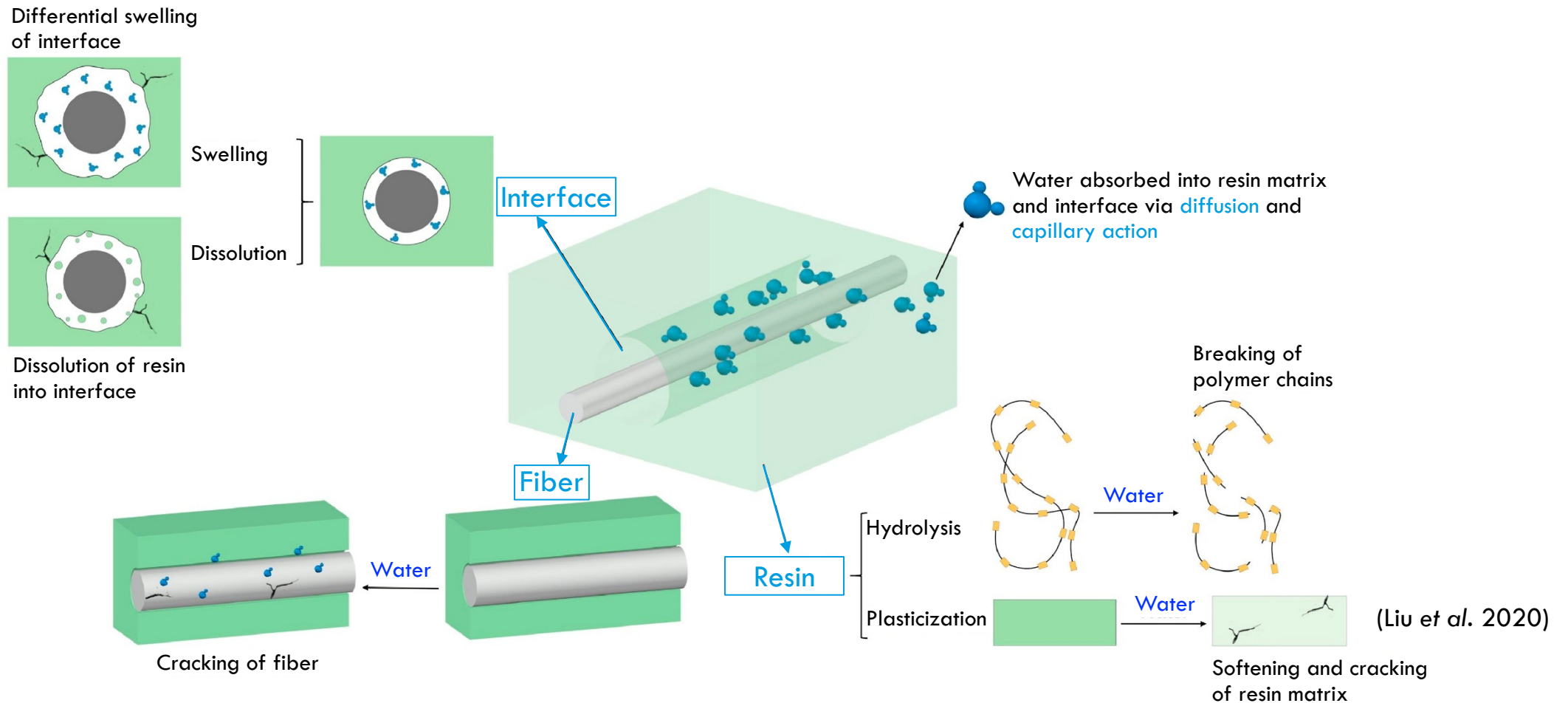
❑ **Physical ageing** refers to **reversible changes** of physical material properties.

❑ **Chemical degradation** causes mostly **irreversible changes** in chain scission and may also affect the interfacial bond and effects at the fibre level.

Durability and long-term behaviour of composites

Durability - Moisture

□ Main degradation mechanisms



Durability and long-term behaviour of composites

Durability - Moisture

□ Main degradation mechanisms

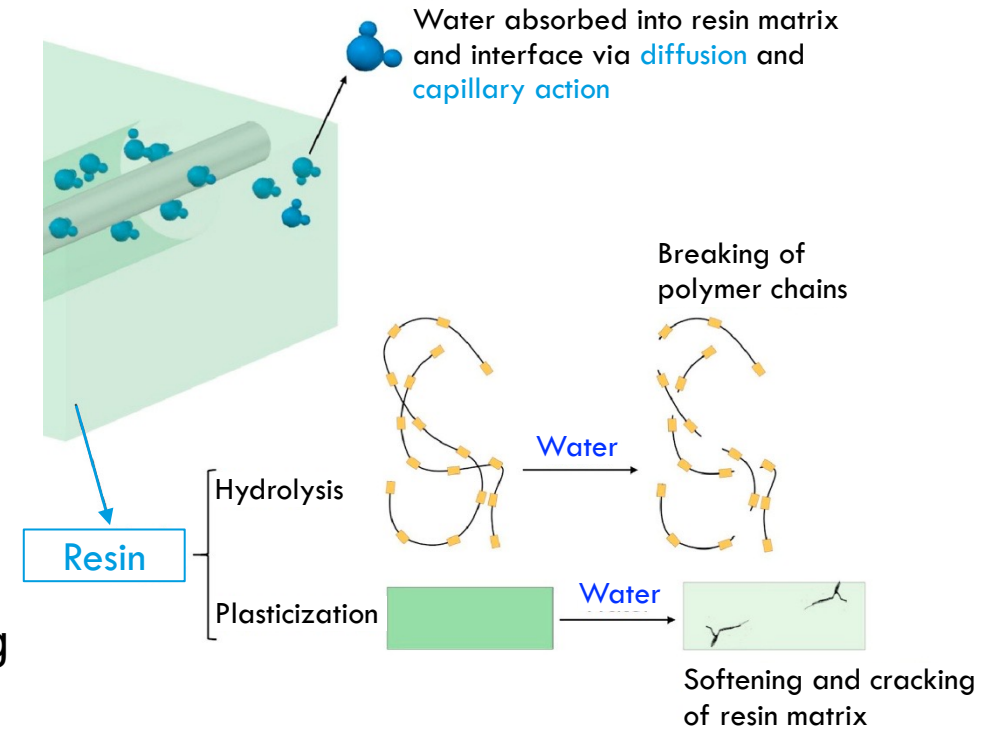
Classification	Degradation Mechanism	Location			Reversibility
		Fibre	Matrix	Interface	
Physical	Plasticization		X	X	Yes (*)
	Swelling		X		Yes (*)
	Relaxation		X		No
Chemical	Hydrolysis				No
	Chain Scission		X		No (*)
	Pitting	X			No (*)
	Debonding			X	No (*)
	Leaching	X	X	X	No

(*) Sometimes is reported as both irreversible and reversible.

Durability - Moisture

□ Main degradation mechanisms

- **Hydrolysis** (irreversible) – **chemical degradation** (reaction), break down of chemical bonds by water molecules.
- **Plasticization** (reversible) – **physical degradation**, incorporation of water molecules into macromolecular chains (voids) of polymer structure.
- **Swelling** (reversible) – **physical degradation**, volumetric changes due to moisture absorption.
- **Relaxation** (irreversible) – comprises the redistribution of the voids and free volumes in the polymer network due to swelling effects, forcing macro-molecular movement.

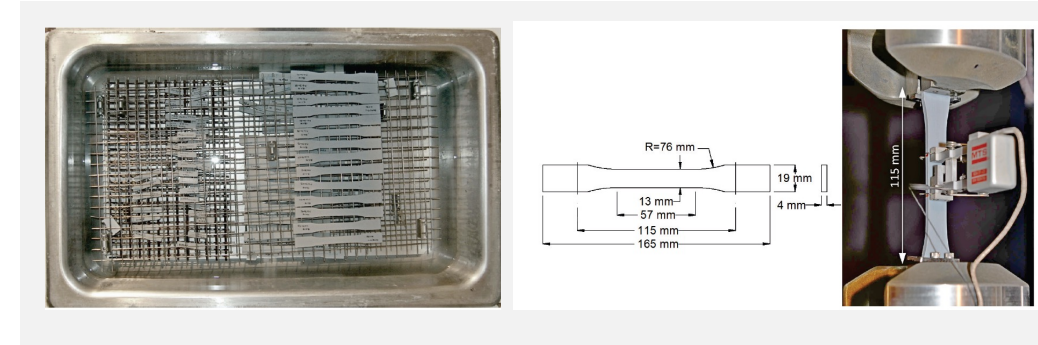


(Liu *et al.* 2020)

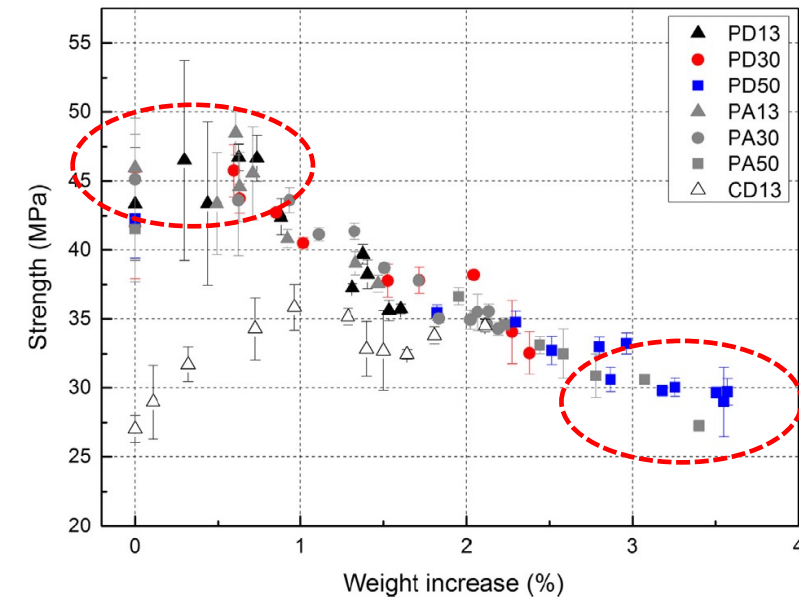
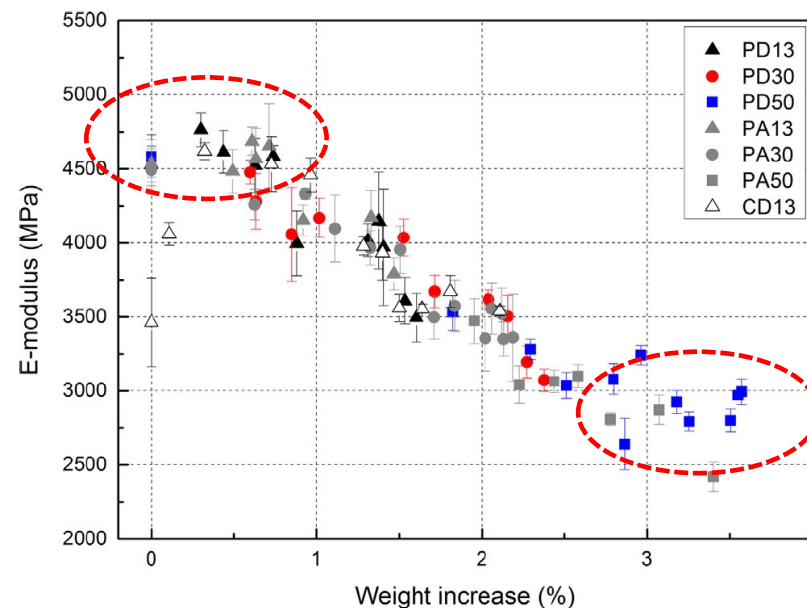
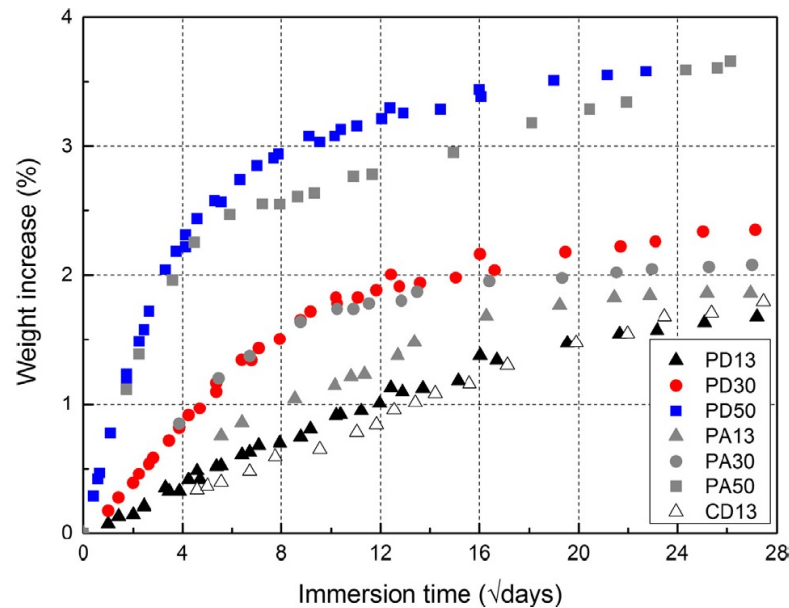
Durability and long-term behaviour of composites

Durability - Moisture

Effects on resins



Example of an epoxy adhesive: Sikadur 330



Source: Savvilitidou, M.; Vassilopoulos, A.P.; Frigione, M.; Keller, T. (2017) "Development of physical and mechanical properties of a cold-curing structural adhesive in a wet bridge environment." *Construction and Building Materials*, 144: 115–124.

Durability - Moisture

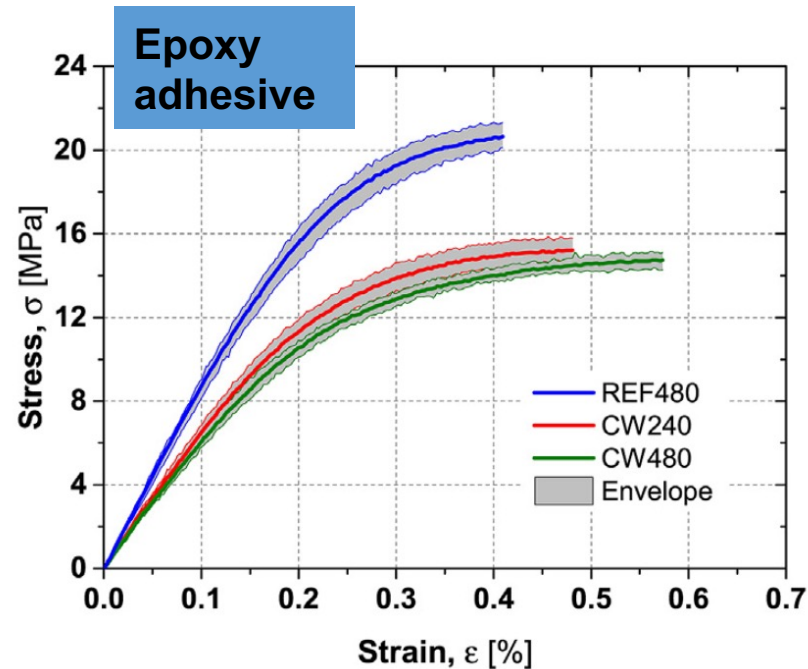
□ Effects on FRP composite materials

- Mechanical properties of composite materials **can be significantly affected by the presence of moisture**, as a result of the degradation of the matrix, the fibres and the interphase.
- **Degradation of composite materials** is generally **less sensitive** when compared to that experienced by the **corresponding neat resins** due to the presence of the **fibre reinforcement**.
- **Reductions** in longitudinal and transverse tensile, compressive, shear and flexural **properties** due to moisture exposure are **frequently reported in the literature**.
- Effects of moisture-related degradation are **more significant for strength than for stiffness**, with changes in modulus generally being very small (typically in the order of 10% over a period of 10-15 years).
- Since the **polymer matrix is more sensitive to moisture than the reinforcing fibres**, matrix dominated properties are typically more affected than fibre dominated properties.

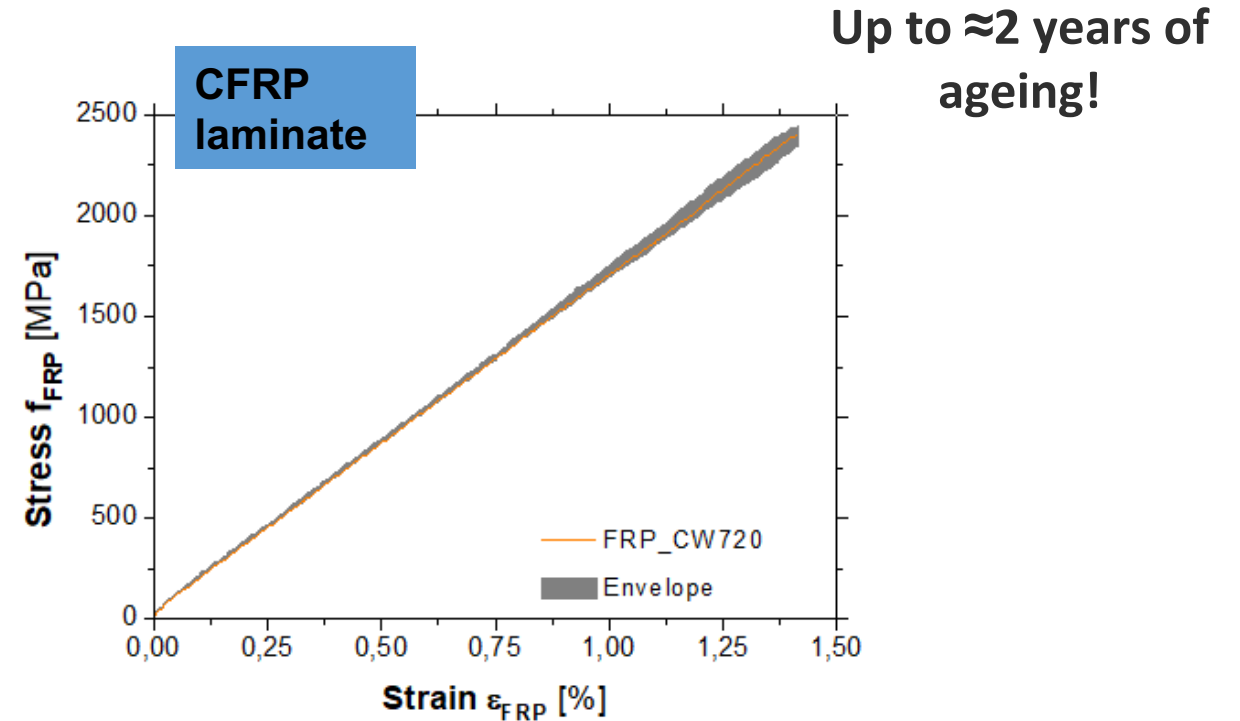
Durability and long-term behaviour of composites

Durability - Moisture

□ Example of epoxy adhesive vs. CFRP laminate



$E_{\text{epoxy}} \searrow -35\%$ $f_{\text{epoxy}} \searrow -28\%$



$E_{\text{CFRP}} \searrow -1\%$ $f_{\text{CFRP}} \searrow -7\%$

Up to ≈ 2 years of ageing!

Source: Silva, P.; Fernandes, P.; Sena-Cruz, J.; Xavier, J.; Castro, F.; Soares, D.; Carneiro, V. (2016) "Effects of different environmental conditions on the mechanical characteristics of a structural epoxy." Composites Part B: Engineering, 88: 55–63. Fernandes, P.; Silva, P.; Correia, L.; Sena-Cruz, J. (2015) "Durability of an epoxy adhesive and a CFRP laminate under different exposure conditions", SMAR2015 – Third Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures, September 7th – 9th, Antalya, 8 pp

Durability and long-term behaviour of composites

Durability - Moisture

□ Mitigation measures

The strategies delay degradation of FRP composite materials against moisture include:

1. Proper **material selection**:

Typically: polyester (ortho < isophthalic) < vinylester < epoxy).

2. Compatibility and proper **embedment of fibres** in resin.

3. Surface with **resin-rich layer**.

4. Proper **quality control** during processing.

5. Depending on the aggressiveness of the exposure, the moisture ingress into the FRP material can be delayed through the use of protective coatings, namely **gel coats and coatings**.



Durability - Chemicals

- ❑ **Composite materials have been successful used in aggressive chemical environments**, in a wide range of sectors of the chemical industry (such as water treatment, paper, food processing, pharmaceutical power generation) for the last 50 years, as chemical-resistant materials (particularly GFRP).
- ❑ **Composite materials** (particularly CFRP) have also been used in the **aerospace industry** for many years, and with an **extensive research related to the chemical resistance**.
- ❑ However, as explained before, **there are critical differences among sectors**. Specifications of composite materials for civil-engineering applications **requiring chemical resistance still does not exist!**

Durability - Chemicals

□ Effects on composite materials

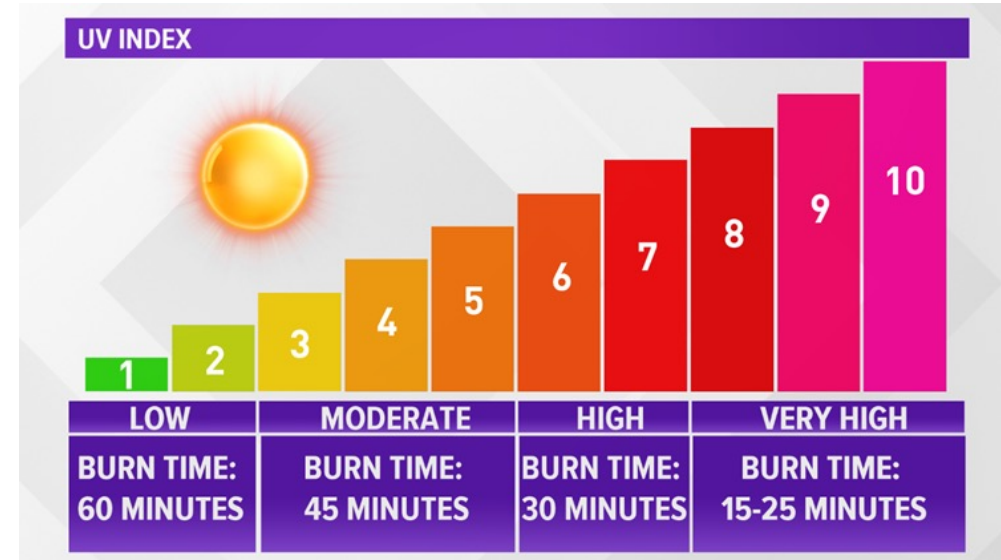
- In several sectors, **there are no standard test methodologies for assessing the chemical resistance of composites.**
- The **right choice** of the FRP composite materials should be done based on:
 - the particularities of the chemical environment;
 - the service temperatures;
 - the exposure profile;
 - the existence of synergistic effects.

Durability and long-term behaviour of composites

Durability - UV radiation

□ Overall

- **Outdoor composite structures** can be exposed to the **ultraviolet (UV) radiation** from the sun.
- **UV radiation affects mainly the polymer matrix** of composite materials. This may yield to detrimental in the overall mechanical properties of composite materials.
- Results show that the effects of exposure of **composite materials to UV radiation on are usually confined to the top few microns of the surface**, affecting especially their aesthetical properties: loss of gloss and discolouration.
- However, when the severity is high, additional problems may occur:
 - stress concentrators and initiate fracture at much lower stress levels;
 - ingress of moisture.

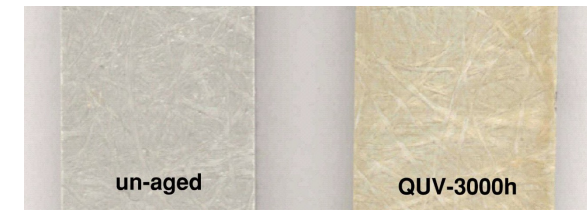


Durability - UV radiation

□ Effects of the on FRP composite materials

UV-induced degradation in FRP composite materials typically occurs according to the following sequence:

- Loss of surface gloss
- Surface discoloration
- Chalking
- Flaking of surface resin
- Pitting
- Microcracking
- Blistering
- Severe loss of resin from outer surface, fibres not yet visible
- Severe loss of resin from outer surface, fibres visible (blooming)
- Fibres visible and loosened from the surface
- Delamination of topmost ply



Loss of surface gloss and surface discoloration



Fibre blooming

Durability and long-term behaviour of composites

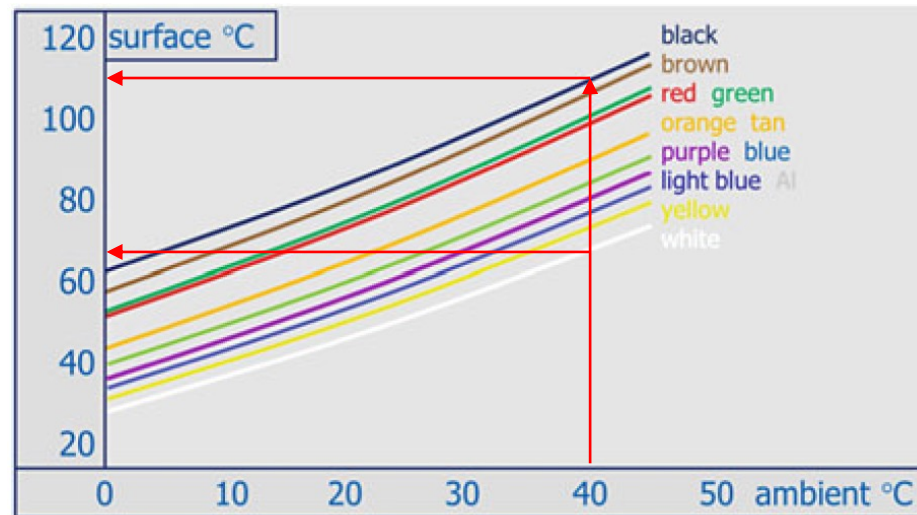
Durability - UV radiation

□ Mitigation measures

The **strategies delay photodegradation** of composite materials against UV exposure include:

- i. Introduction of **stabilizers** into the polymer matrix
 - Controlling the amount of radiation reaching the polymer
 - Inhibiting chemical reactions started by radiation absorption
- ii. Application of **surface protections** of the FRP components, namely **gel coats or appropriate paints**.

The effect of direct sunlight on the surface temperature of different coloured objects



Source: P. Davies, Y.D.S. Rajapakse. Durability of Composites in a Marine Environment, Springer, 2014.

Section 2.2

**How durability can be addressed by the
European Standard CEN/TS 19901:2022**

Durability and long-term behaviour of composites

How durability can be addressed by the codes - CEN/TS 19101: 2022

TECHNICAL SPECIFICATION **CEN/TS 19101**
SPÉCIFICATION TECHNIQUE
TECHNISCHE SPEZIFIKATION October 2022

ICS 91.01.03.0

English Version

Design of fibre-polymer composite structures


Calcul des structures en matériaux composites Bemessung von Tragwerken aus Faserverbund-Kunststoffen

This Technical Specification (CEN/TS) was approved by CEN on 22 August 2022 for provisional application.

The period of validity of this CEN/TS is limited initially to three years. After two years the members of CEN will be requested to submit their comments, particularly on the question whether the CEN/TS can be converted into a European Standard.

CEN members are required to announce the existence of this CEN/TS in the same way as for an EN and to make the CEN/TS available promptly at national level in an appropriate form. It is permissible to keep conflicting national standards in force (in parallel to the CEN/TS) until the final decision about the possible conversion of the CEN/TS into an EN is reached.

CEN members are the national standards bodies of Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Republic of North Macedonia, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Türkiye and United Kingdom.




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**DESIGN OF
FIBRE-POLYMER
COMPOSITE STRUCTURES**
Commentary to European Technical
Specification CEN/TS 19101: 2022



Σ Π Ω
I H EUROCODES
E Y

EDITED BY JOÃO R. CORREIA, THOMAS KELLER,
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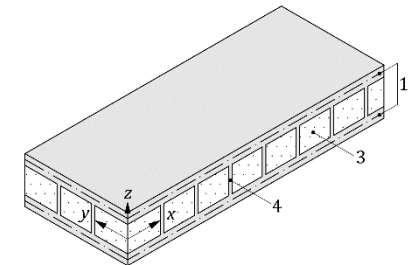
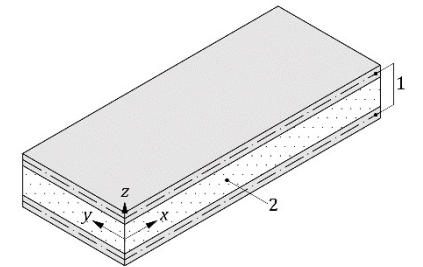
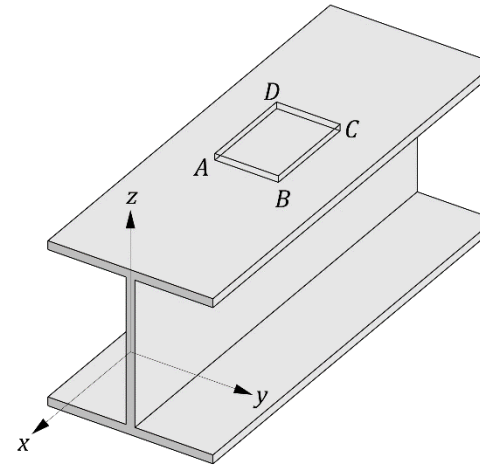
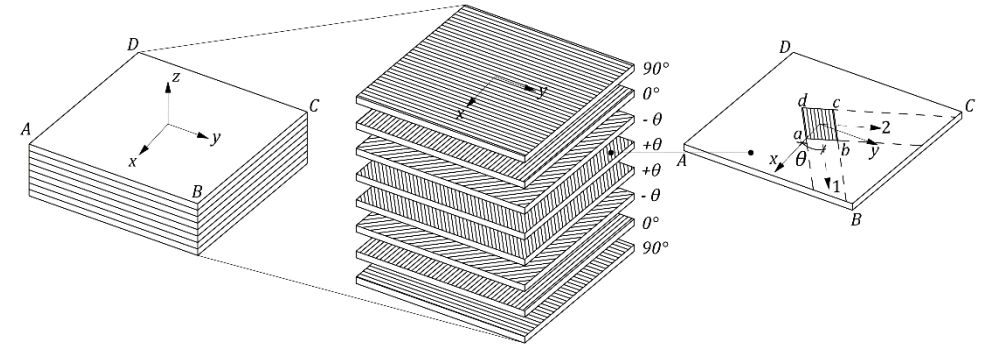
OPEN ACCESS

<https://doi.org/10.1201/9781032706948>

Durability and long-term behaviour of composites

CEN/TS 19101:2022 - Scope

- ❑ The TS is applicable to:
 - Buildings, bridges, other civil engineering structures
 - Permanent, temporary structures
 - All-composite structures, hybrid-composite structures
 - Laminates, profiles, sandwich panels
 - Joints: Bolted, bonded
 - Constituent materials:
 - Glass, carbon, basalt, aramid fibres
 - Thermoset resins and adhesives
 - Polymeric foam, balsa wood cores



Durability and long-term behaviour of composites

How durability can be addressed by the codes - CEN/TS 19101: 2022

- Therefore, **nominal conversion factors** that account for the **effects of temperature and moisture** on material properties are included in the **European Technical Specification (TS) FprCEN/TS 19101 Design of Fibre-Polymer Composite Structures**, for i) **composite materials**, ii) **sandwich core materials** and iii) **epoxy adhesives**.
- The **design resistances**:

$$R_d = \frac{1}{\gamma_{Rd} \cdot \gamma_m} R \left\{ \eta_{c,i} X_{k,i}; a_d; \sum F_{Ed} \right\}$$

*Composite components, and members,
bolted connections and joints*

$$R_d = R \left\{ \eta_{c,j} \frac{X_{k,j}}{\gamma_M}; a_d; \sum F_{Ed} \right\}$$

*Creep rupture, fatigue, adhesive
connections, and fire*

Durability and long-term behaviour of composites

How durability can be addressed by the codes - CEN/TS 19101: 2022

□ Format of the design considering temperature and moisture effects

- The changes in the mechanical properties of composite materials, sandwich core materials and adhesives, due to **temperature and moisture effects** through the **conversion factor**, η_c , given by:

$$\eta_c = \eta_{ct} \cdot \eta_{cm}$$

The diagram shows the equation $\eta_c = \eta_{ct} \cdot \eta_{cm}$ enclosed in a red dashed box. Two arrows originate from the box: one points to the text 'Conversion factor for temperature effects' and the other points to 'Conversion factor for moisture effects'.

η_{ct} accounts for **short-term changes** due to temperature effect

η_{cm} accounts for **changes due to moisture absorption over time**, including ageing effects resulting from **long-term exposure, for specific environmental conditions and a 50-year service life**

Durability and long-term behaviour of composites

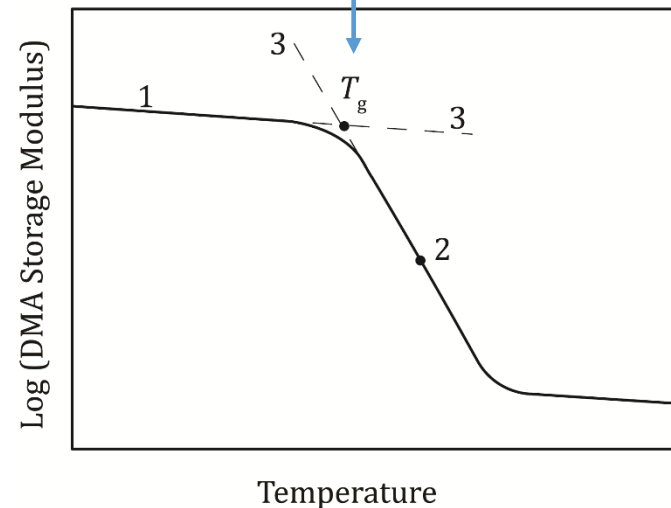
How durability can be addressed by the codes - CEN/TS 19101: 2022

□ Format of the design considering temperature and moisture effects

- The TS limits the maximum material temperature in service conditions, T_s , in members, joints and components:

$$-40\text{ }^{\circ}\text{C} < T_s < T_g - 20\text{ }^{\circ}\text{C}$$

The glass transition temperature (T_g) of composite, polymeric core and adhesive materials according to the TS (ISO 6721-11):



How durability can be addressed by the codes - CEN/TS 19101: 2022

□ Format of the design considering temperature and moisture effects

- The **TS** limits the maximum material temperature in service conditions, T_s , in members, joints and components:

$$-40\text{ °C} < T_s < T_g - 20\text{ °C}$$

Rationale:

- The imposed **lower bound** ($-40\text{ °C} < T_s$) → literature shows **limited reductions** in different mechanical properties at **sub-zero temperatures down to -40 °C**
- The imposed **upper bound** ($T_s < T_g - 20\text{ °C}$) → **relevant reduction in the short-term mechanical properties** and the **significant increase in viscoelasticity of composites, cores and adhesive materials** when temperatures approach the T_g .

Durability and long-term behaviour of composites

How durability can be addressed by the codes - CEN/TS 19101: 2022

□ Conversion factor for temperature

The **conversion factor for temperature**, η_{ct} , is determined according to the following general equation, considering a **reference material temperature** of 20 °C:

$$\eta_{ct} = \min \left\{ 1,0 - \alpha \cdot \frac{T_s - 20 \text{ °C}}{T_g - 20 \text{ °C}}; 1,0 \right\}$$

Example: what are the variation of the properties of a composite ($T_g=100 \text{ °C}$) submitted to a service temperature of 50 °C?

α	Composite materials, sandwich core materials and adhesives
0,25	For fibre-dominated properties of composite materials with glass, carbon or basalt fibres and thermoset polymer matrix of either unsaturated polyester, vinylester or epoxy
0,80	For matrix-dominated properties of composite materials with glass, carbon or basalt fibres and thermoset polymer matrix of either unsaturated polyester, vinylester or epoxy
0,46	For polymeric foam core materials , namely polyurethane (PUR), polyethylene terephthalate (PET) and polyvinyl chloride (PVC) foams (densities from 40 to 300 kg/m ³)
0,85	For epoxy adhesives

Durability and long-term behaviour of composites

How durability can be addressed by the codes - CEN/TS 19101: 2022

□ Conversion factor for moisture

The **conversion factor for moisture**, η_{cm} , for **unprotected composite materials** (glass, carbon or basalt fibres; thermoset polymer matrix of unsaturated polyester, vinylester or epoxy; fibre volume fraction of at least 35%) and **epoxy adhesives**:

Example: what are the variation of the properties of a composite ($T_g=100\text{ °C}$) submitted to a service temperature of 50 °C under outdoor exposure?

Exposure classes	Influence of moisture	η_{cm}
I	Indoor exposure with service temperature	1,0
II	Outdoors exposure with service temperature, without (i) continuous exposure to water, (ii) permanent immersion in water, (iii) permanent exposure to a relative humidity higher than 80%, (iv) combined UV-radiation and frequent freeze-thaw cycles	0,85
III	Continuous exposure to water (or seawater), or permanent immersion in water (or seawater), or permanent exposure to a relative humidity higher than 80% (material temperature up to 25 °C)	0,60

Section 3

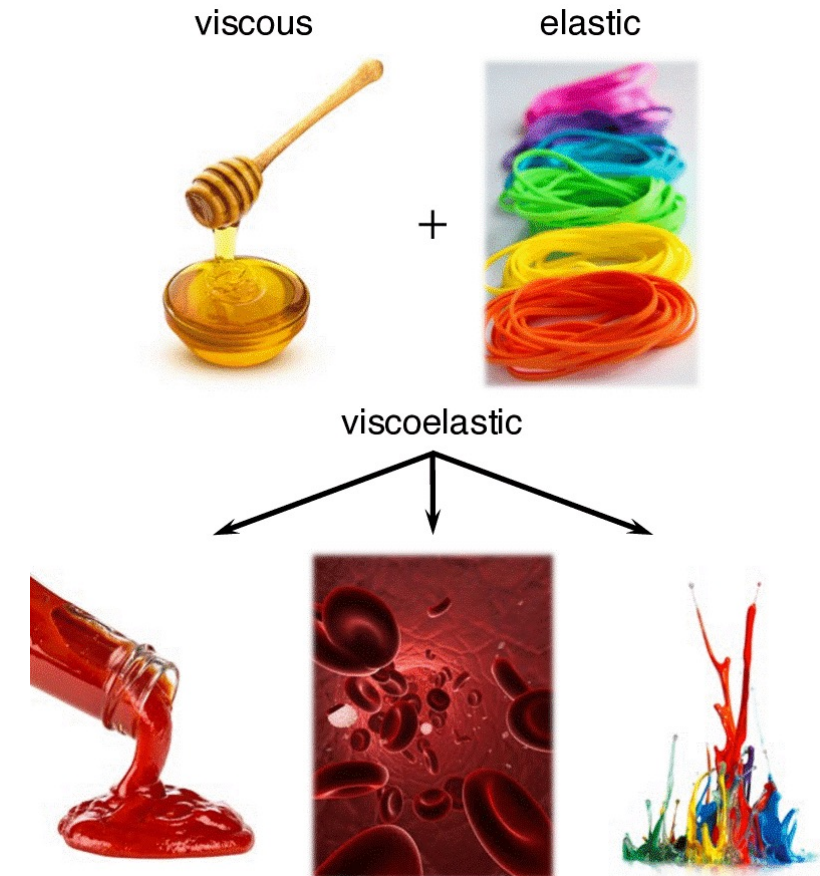
Viscoelasticity

Section 3.1

Introduction

What is Viscoelasticity?

- **Viscoelasticity** is the property of materials that exhibit both **viscous** and **elastic** characteristics when undergoing deformation (during the time):
 - A **viscous material** exhibits **time dependent behavior**: when a constant stress is applied it deforms at a constant rate. When the load is removed, the material has 'forgotten' its original configuration, remaining in the deformed state.
 - An **elastic material** deforms **instantaneously when stressed** and 'remembers' its original configuration, returning instantaneously to its original state once the stress is removed.

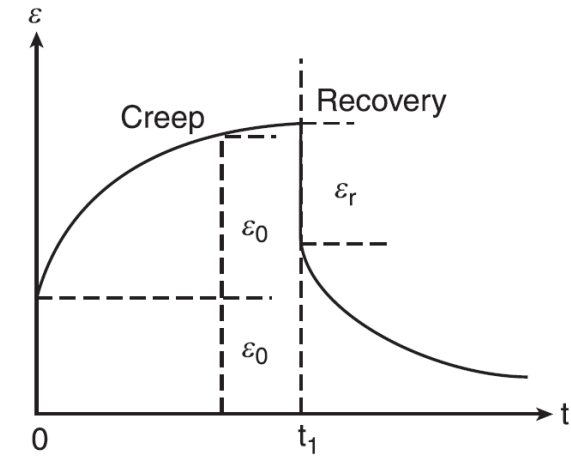
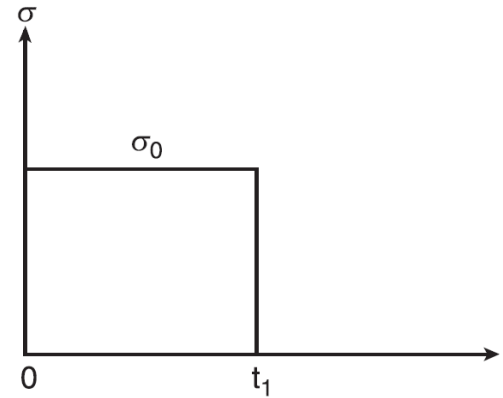


Source: J Berner. Out of Equilibrium Dynamics of Driven Colloids in Viscoelastic Media. Dissertation for the degree of Doctor of Natural Sciences, University of Konstanz, 2020.

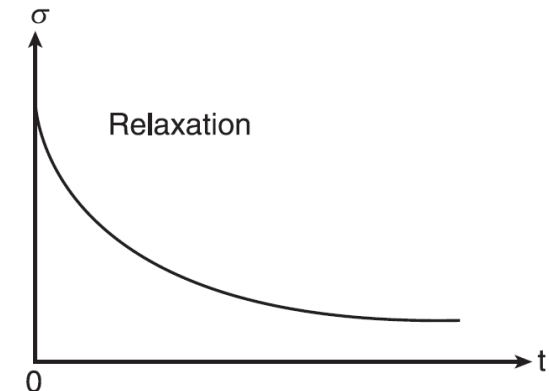
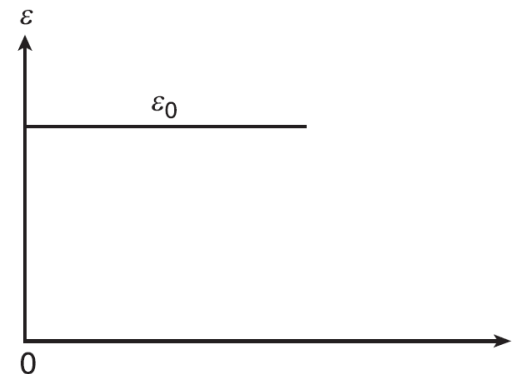
Durability and long-term behaviour of composites

What is Creep? What is Relaxation?

□ **Creep** is a slow and continuous deformation of a material under constant stress.



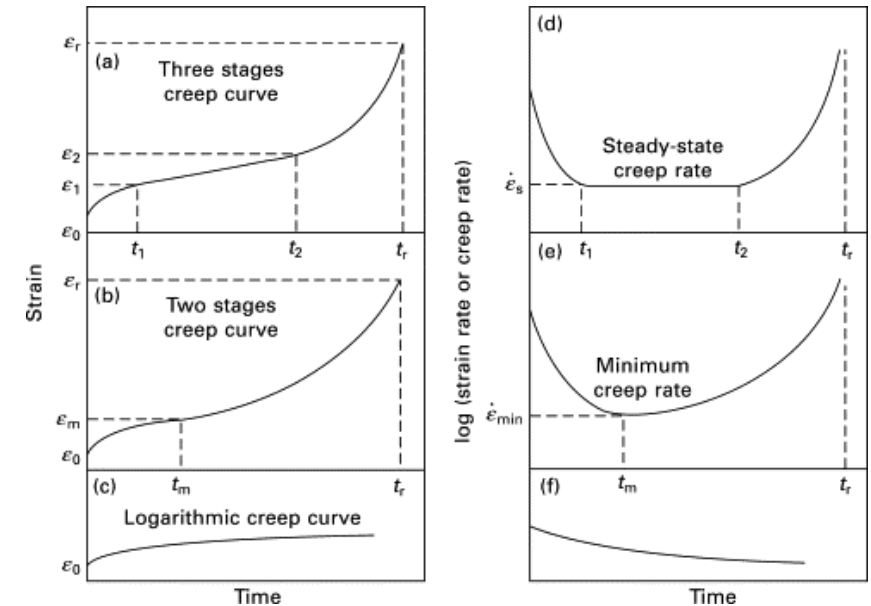
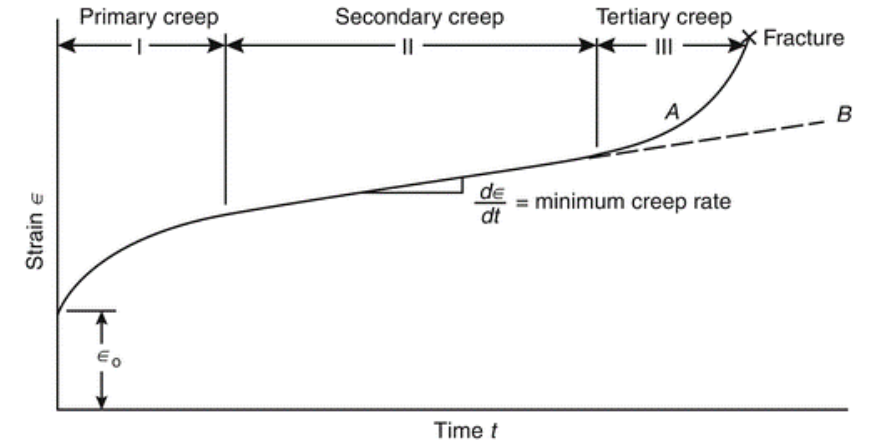
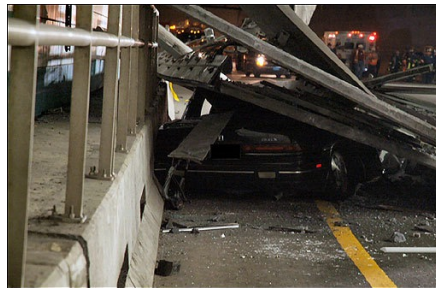
□ **Relaxation** is a gradual and continuous stress decrease under constant strain.



Durability and long-term behaviour of composites

Creep stages

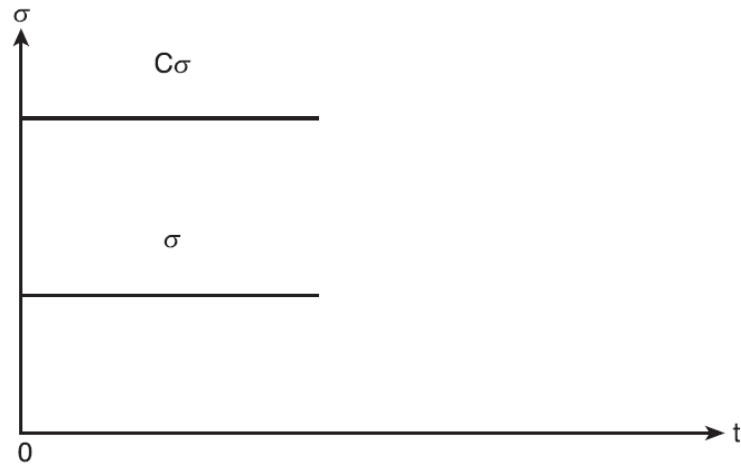
- ❑ **Primary creep:** the material undergoes deformation at a decreasing rate
- ❑ **Secondary creep:** the material progresses at a nearly constant rate
- ❑ **Tertiary creep:** it occurs at an increasing rate and ends with **fracture** of the material



Durability and long-term behaviour of composites

Linearity in creep: Homogeneity + Superposition Principle

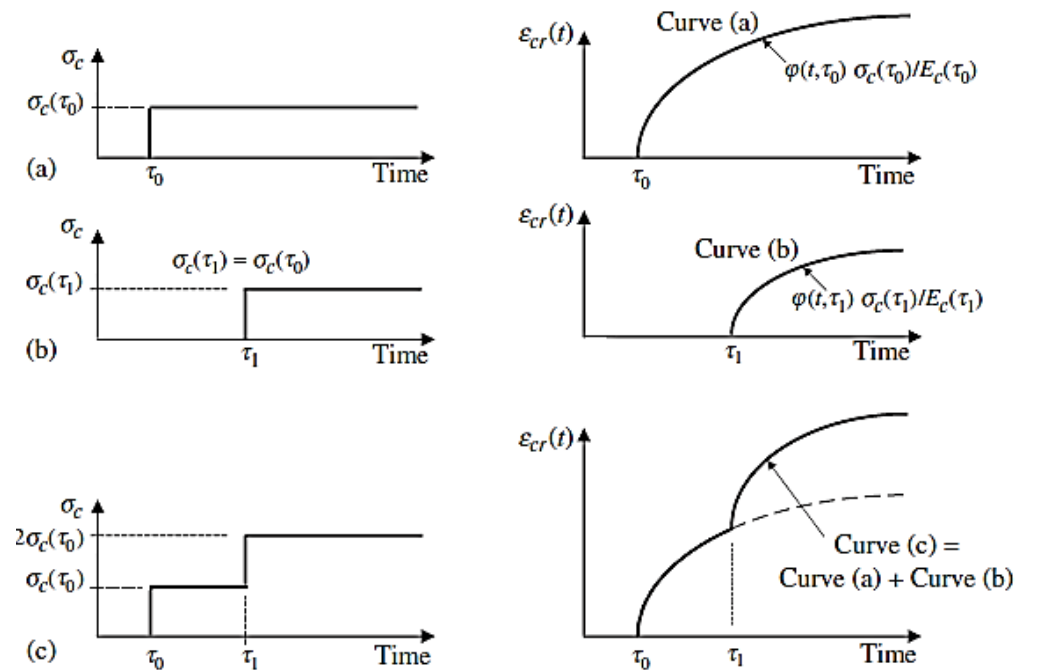
Homogeneity



$$\varepsilon_x \{ c\sigma_x \} = c\varepsilon_x \{ \sigma_x \}$$

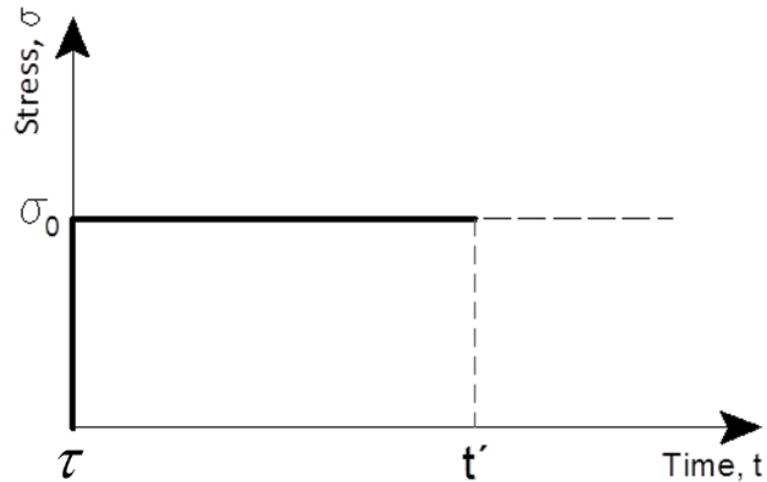
$$c = \text{const}$$

Superposition Principle



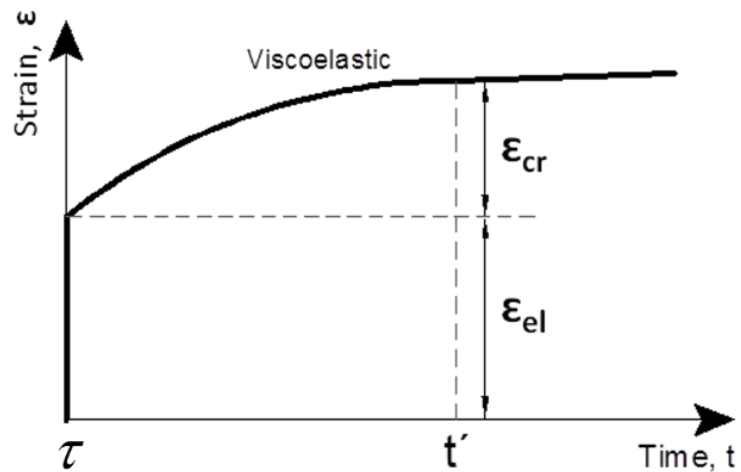
$$\varepsilon_x (\sigma_x^1 + \sigma_x^2) = \varepsilon_x \{ \sigma_x^1 \} + \varepsilon_x \{ \sigma_x^2 \}$$

Creep: Creep coefficient ($\phi(t)$)



$$\phi(t) = \frac{\delta_{\text{creep}}(t)}{\delta_{\text{elast}}}$$

$$\delta(t) = \delta_{\text{elast}} + \delta_{\text{creep}}(t) \rightarrow \delta(t) = \delta_{\text{elast}} \cdot (1 + \phi(t))$$



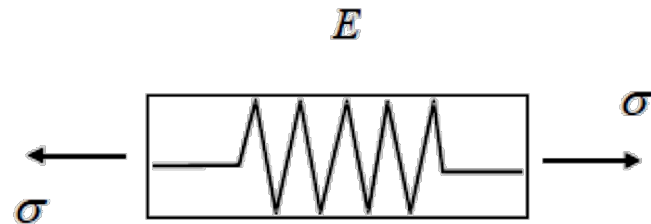
$$\delta = \frac{\text{Const.}}{E} \rightarrow \delta(t) = \frac{\text{Const.}}{E_{\text{elast}}} \cdot (1 + \phi(t)) = \frac{\text{Const.}}{\frac{E_{\text{elast}}}{1 + \phi(t)}} = \frac{\text{Const.}}{E(t)}$$

Age-adjusted Effective Modulus Method (AAEM):

$$E(t) = \frac{E_{\text{elast}}}{1 + \phi(t)}$$

Rheological Models: Basic components

Linear elastic spring

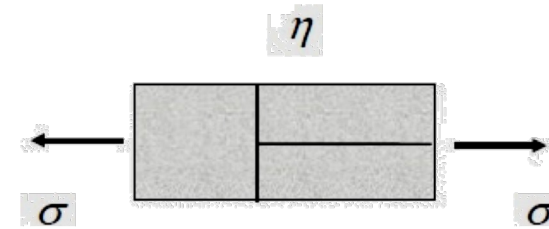


Hooke Model – typical of solids

$$\varepsilon = \frac{1}{E} \cdot \sigma$$

ε – deformation, strain
 E – elastic modulus

Linear viscous dash-pot



Newton Model – typical of flows

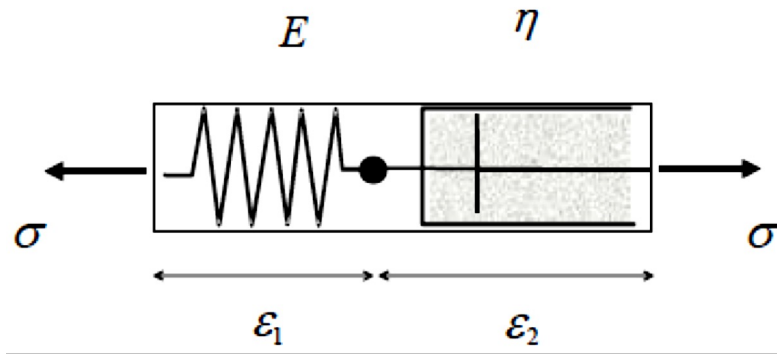
$$\dot{\varepsilon} = \frac{1}{\eta} \cdot \sigma$$

σ – stress applied
 η – viscosity

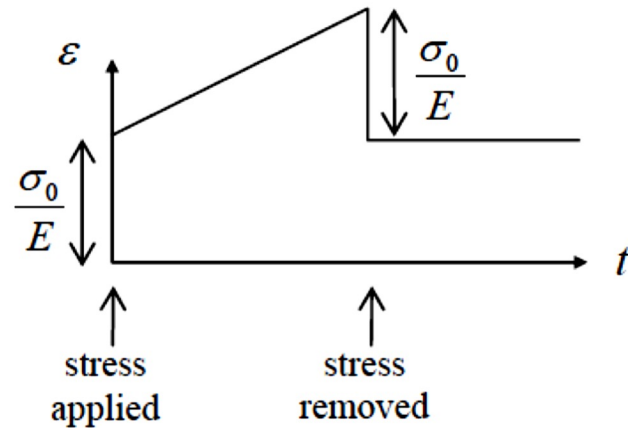
Durability and long-term behaviour of composites

Rheological Models: Basic components

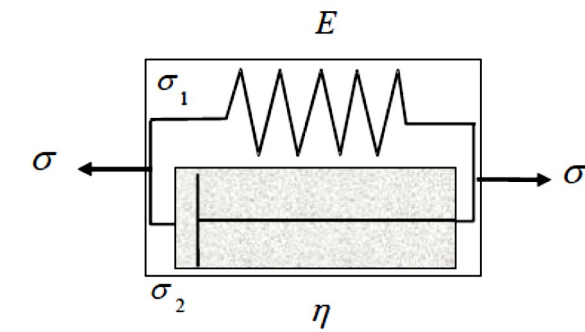
Maxwell fluid model



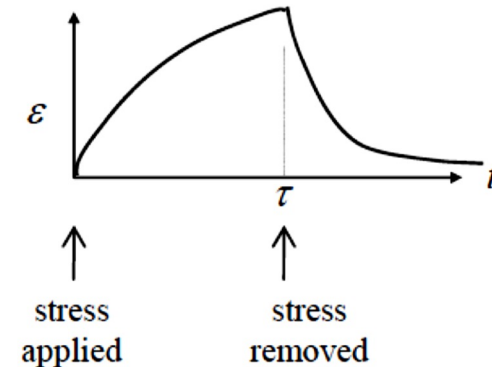
$$\dot{\epsilon}(t) = \frac{\dot{\sigma}(t)}{E} + \frac{\sigma(t)}{\eta}$$



Kelvin (Voigt) solid model

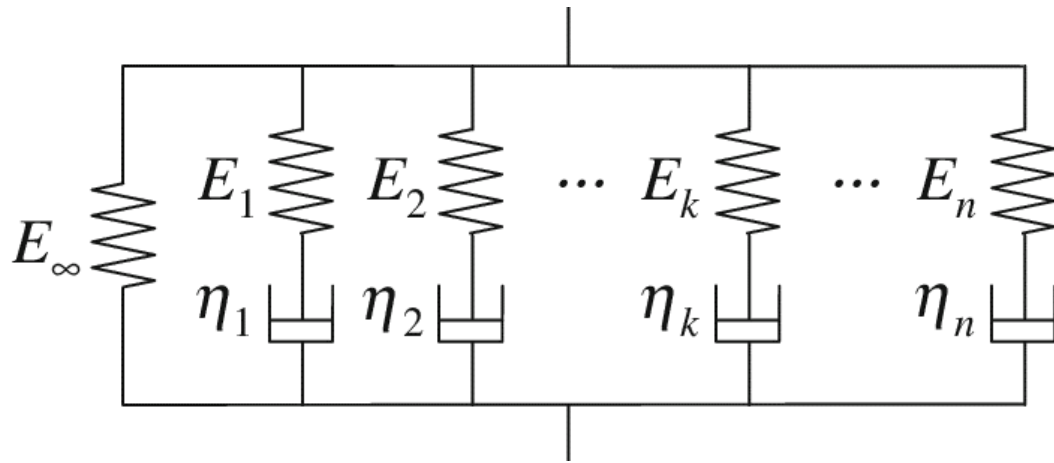


$$\dot{\epsilon}(t) = \frac{\sigma(t)}{\eta} + \frac{E \cdot \epsilon(t)}{\eta}$$

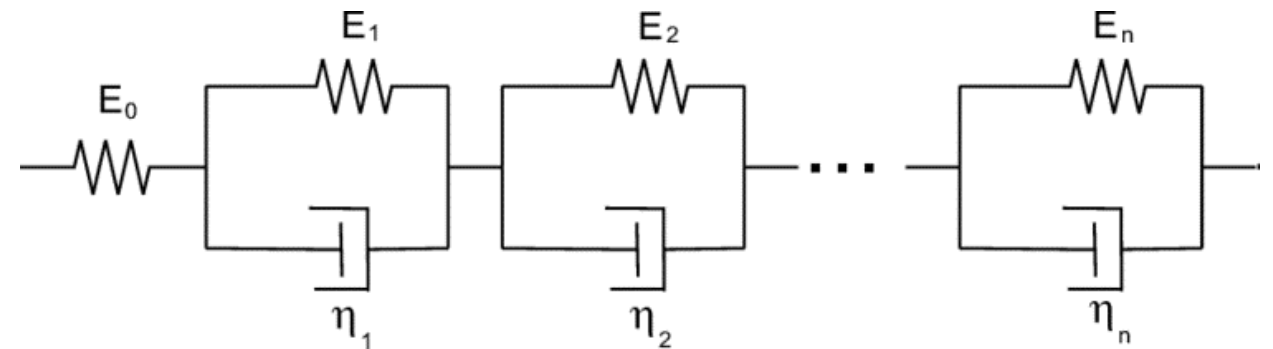


Rheological Models

Maxwell generalized model

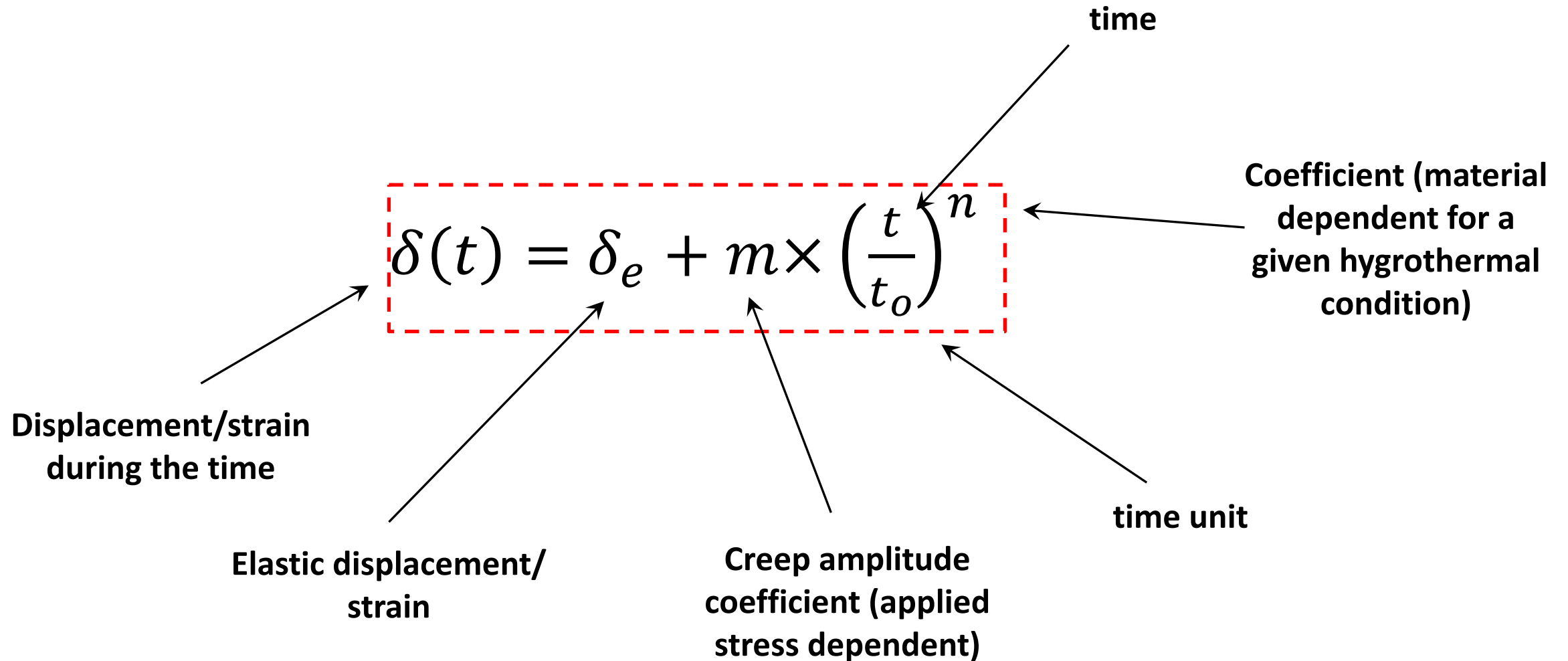


Kelvin generalized model



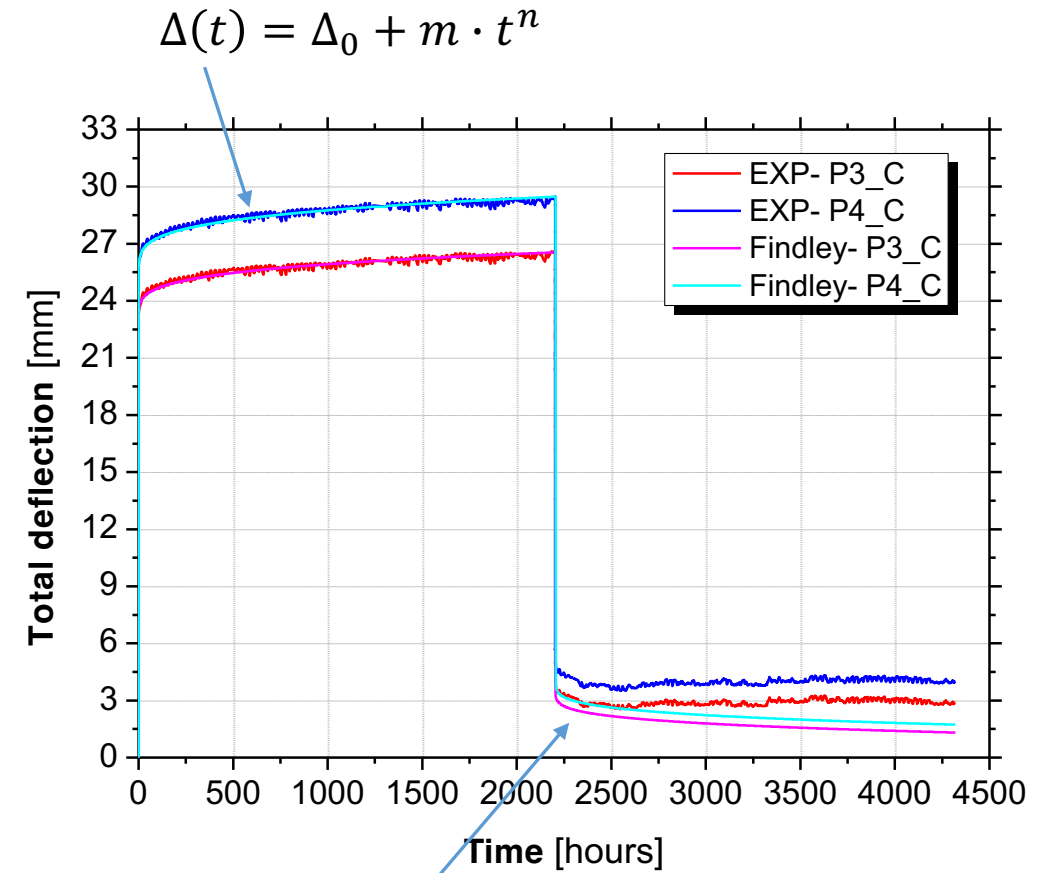
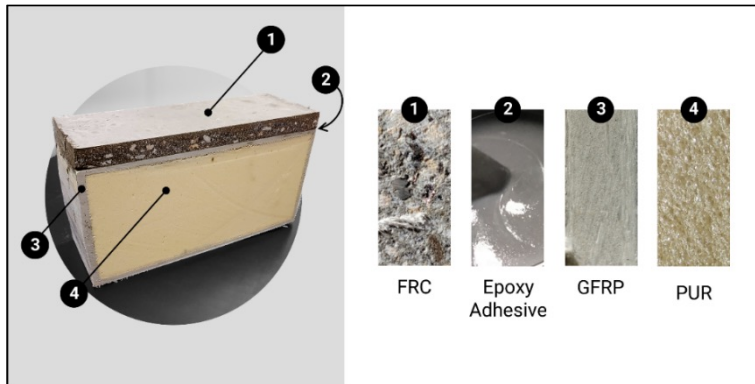
Durability and long-term behaviour of composites

Creep Model for Composite Materials: Findley's power law



Durability and long-term behaviour of composites

Creep Model for Composite Materials: Findley's power law



Source: Silva, T.; Correia, L.; Dehshirizadeh, M.; Sena-Cruz, J. (2022) "Flexural Creep Response of Hybrid GFRP-FRC Sandwich Panels." Materials, 15: 2536, 25 pp. DOI: 10.3390/ma15072536

$$\Delta(t) = m \cdot (t_{un})^n + m_{un} \cdot (t - t_{un})^n$$

Creep in composites

- ❑ The **creep in composites depends on several factors**, including:
 - The **environmental conditions** (temperature and relative humidity)
 - The **type of loading**
 - The **stress level**

- ❑ For **composite sandwich panels**, creep **deformations due to shear** are generally **more significant than those due to bending**, especially in homogeneous-core sandwich panels.

- ❑ For **composite materials** and **polymeric foam core materials**, in general, **linear viscoelasticity applies for relatively low stresses** (for composite materials with glass fibres, typically up to **25% to 30% of the short-term strength**).

Creep in composites

- ❑ In general, the **viscoelasticity** of composite, core and adhesive materials **increases** with **increasing temperature and relative humidity**.
- ❑ For composite materials, the **creep coefficient decreases** with **increasing fibre content along the direction of the applied stresses**.
- ❑ For **polymeric foam core materials**, the **creep coefficient generally decreases with increasing density**, while for end-grain balsa the creep coefficient is independent of density.
- ❑ In addition, the **creep behaviour of polymeric foam core materials is generally orthotropic**.

Section 3.2

**How creep can be addressed by the
CEN/TS 19901:2022**

How creep can be addressed by the codes - CEN/TS 19101:2022

□ Serviceability verification (**Linear creep**)

Creep effects on the **deformations** of composite structures should be taken into account by **reducing the initial mean values of the relevant elastic moduli of materials**, through a **creep coefficient**:

$$X_m(t) = \frac{X_m(0)}{1 + \phi(t)}$$

t = time

$X_m(t)$ = **mean value of elastic or shear modulus** at time to take into account creep effects

$X_m(0)$ = **initial mean value of elastic or shear modulus** (at time '0')

$\phi_m(t)$ = **creep coefficient** at time t

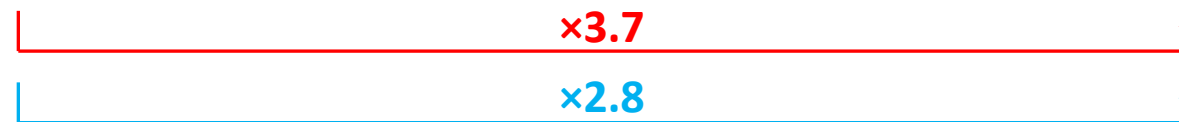
Durability and long-term behaviour of composites

How creep can be addressed by the codes - CEN/TS 19101: 2022

□ Serviceability verification (Linear creep)

Table A.1 — Values for the creep coefficient, $\phi(t)$, for different elastic moduli of pultruded composite profiles (glass, carbon or basalt fibres; fibre volume fraction of at least 35%; temperature up to 25 °C; relative humidity up to 65%)

Property	Period of time (years)										
	1	5	10	15	20	25	30	40	50	75	100
E_x^{full}	0,25	0,38	0,46	0,51	0,55	0,58	0,61	0,66	0,70	0,78	0,84
G_{xy}^{full}	0,57	0,98	1,23	1,40	1,54	1,66	1,76	1,94	2,09	2,39	2,62
$E_{x,t}$	0,20	0,22	0,24	0,24	0,25	0,25	0,25	0,26	0,26	0,27	0,28
$E_{x,c}$	0,20	0,23	0,27	0,30	0,32	0,34	0,36	0,38	0,41	0,45	0,48



Source: CEN/TS 19101: 2022

Durability and long-term behaviour of composites

How creep can be addressed by the codes - CEN/TS 19101: 2022

□ Serviceability verification (Linear creep)

Table A.2 — Values for the creep coefficient, $\phi(t)$, for different elastic moduli of composite laminates/plies (glass, carbon or basalt fibres; fibre volume fraction of at least 35%; temperature up to 25 °C; relative humidity up to 65%)

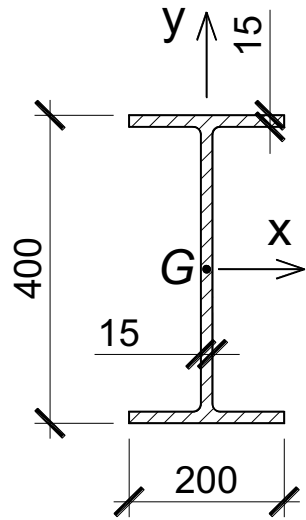
Type of fibres	Property	Period of time (years)										
		1	5	10	15	20	25	30	40	50	75	100
UD	$E_{x,t}$	0,10	0,11	0,12	0,13	0,13	0,13	0,13	0,14	0,14	0,14	0,15
	$E_{x,c}$	0,15	0,23	0,27	0,30	0,32	0,34	0,36	0,38	0,41	0,45	0,48
	G_{xy}	1,13	1,55	1,78	1,94	2,06	2,16	2,25	2,40	2,52	2,78	2,94
Woven (0/90°)	$E_{x,t}, E_{x,c}$	0,44	0,53	0,58	0,60	0,62	0,64	0,65	0,67	0,68	0,71	0,73
CSM	$E_{x,t}, E_{x,c}$	1,48	1,91	2,12	2,25	2,34	2,42	2,48	2,58	2,67	2,82	2,93

Source: CEN/TS 19101: 2022

Durability and long-term behaviour of composites

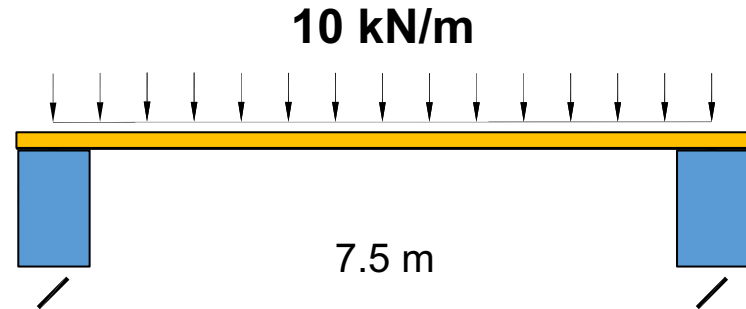
How creep can be addressed by the codes - CEN/TS 19101: 2022

Serviceability verification (Linear creep)



Pultruded GFRP I400 profile:

- $A_{web} = 60 \text{ cm}^2$
- $I_{xG} = 28576.625 \text{ cm}^4$
- $E_L = 30 \text{ GPa}$
- $G_{LT} = 3.5 \text{ GPa}$



Mid-span displacement (mm)

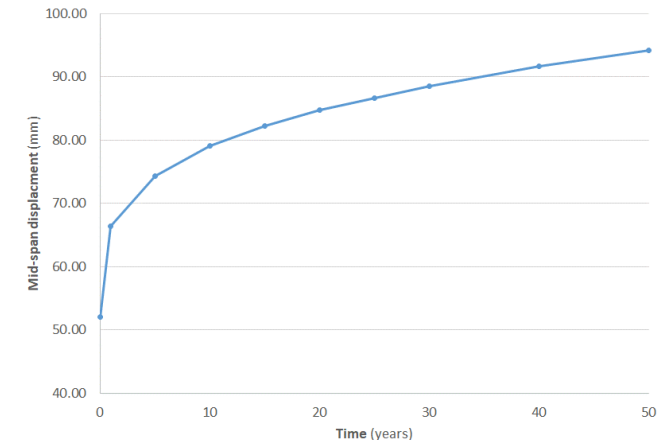
Time (years)	Timoshenko beam				
	Flexural	Shear	Total	Flexural	Shear
0	48.06	4.02	52.07	92.3%	7.7%
1	60.07	6.31	66.38	90.5%	9.5%
5	66.32	7.96	74.27	89.3%	10.7%
10	70.16	8.96	79.12	88.7%	11.3%
25	75.93	10.69	86.62	87.7%	12.3%
50	81.70	12.42	94.11	86.8%	13.2%

(Based on Table A1. of CEN/TS 19101: 2022)

$$\delta(t) = \frac{5}{384} \cdot \frac{p \cdot l^4}{E(t) \cdot I} + \frac{1}{8} \cdot \frac{p \cdot l^2}{G(t) \cdot A'}$$

$$E(t) = \frac{E_L}{1 + \phi_E(t)}$$

$$G(t) = \frac{G_{LT}}{1 + \phi_G(t)}$$



How creep can be addressed by the codes - CEN/TS 19101: 2022

□ Ultimate verification (Creep rupture)

Creep rupture of composite members and components can be prevented by limiting sustained stresses, under the quasi-permanent combination of actions, as follows:

Traction

$$\sigma_{t,creep,Ed} \leq \sigma_{t,creep,Rd}$$

$$\sigma_{t,creep,Rd} = \frac{\eta_c}{\gamma_{M,creep}} \cdot k_{t,creep} \cdot f_{i,t,k}$$

(=1,5)

Compression

$$\sigma_{c,creep,Ed} \leq \sigma_{c,creep,Rd}$$

$$\sigma_{c,creep,Rd} = \frac{\eta_c}{\gamma_{M,creep}} \cdot k_{c,creep} \cdot f_{i,c,k}$$

(=1,5)

Durability and long-term behaviour of composites

How creep can be addressed by the codes - CEN/TS 19101: 2022

□ Ultimate verification (Creep rupture)

Strength reduction factors ($k_{t,creep}$ and $k_{c,creep}$) for 50 years:

Type of stress	Glass	Aramid	Basalt	Carbon
Tensile	0.4	0.5	0.6	0.9
Compressive	0.75×0.4	0.75×0.5	0.75×0.6	0.75×0.9

- G, A, C: strength reduction factors derived from an extensive literature review
- B: reduced existing data + engineering judgement
- A, B, C: values also valid for 100 years
- G: $k_{t,creep}(t) = 0.9 - 0.088 \cdot \lg(t)$; $k_{c,creep}(t) = 0.75 \cdot k_{t,creep}(t)$
- $k_{c,creep} = 0.75 \times k_{t,creep}$: reduced existing data + engineering judgement

Durability and long-term behaviour of composites



Many thanks!

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